



Strong Interactions: Open Questions and New Ideas

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Where do we stand?

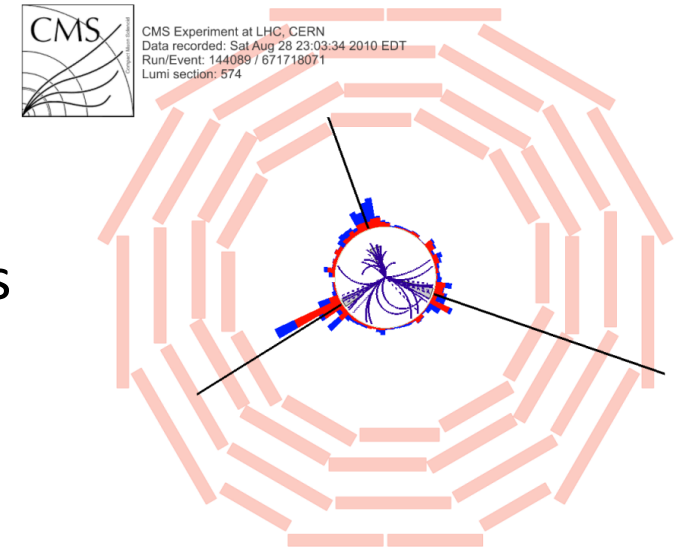
- QCD firmly established as theory of strong interactions
- Remarkably simple Lagrange density

$$\mathcal{L}_{\text{QCD}} = -\frac{1}{4}F_{\mu\nu}^a F_a^{\mu\nu} + \bar{\psi}(i\not{D} - m)\psi$$

- Enormously rich phenomenology
- Many successful qualitative explanations and predictions
- Quantitative understanding not always feasible

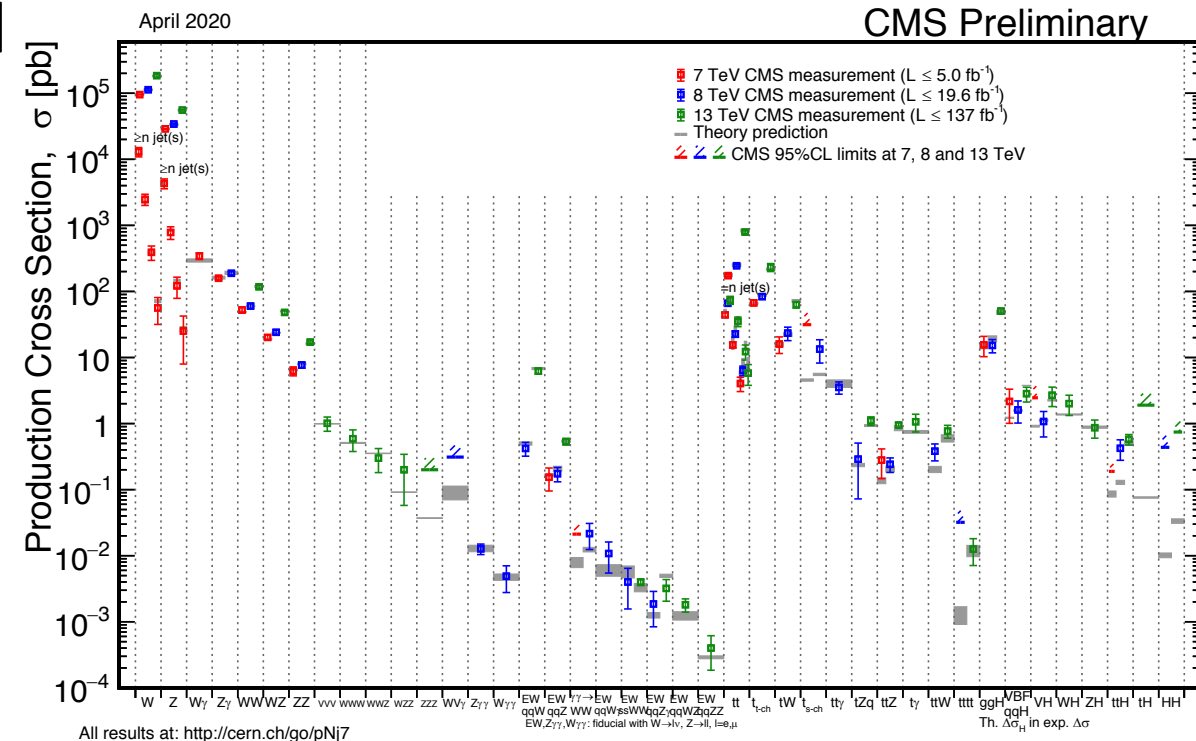
Where do we stand?

- QCD at high energies: weak coupling and asymptotic freedom
 - Perturbative QCD as quantitative framework
 - Dynamics of quarks and gluons
 - Jet observables were early test of QCD
 - Factorization separates weak from strong coupling effects
- Quantitative predictions
 - Multi-loop calculations for inclusive quantities
 - Higher orders (NLO, NNLO, ...), resummation and parton shower simulation
 - Strong coupling dynamics parametrized in parton distributions, hadronization



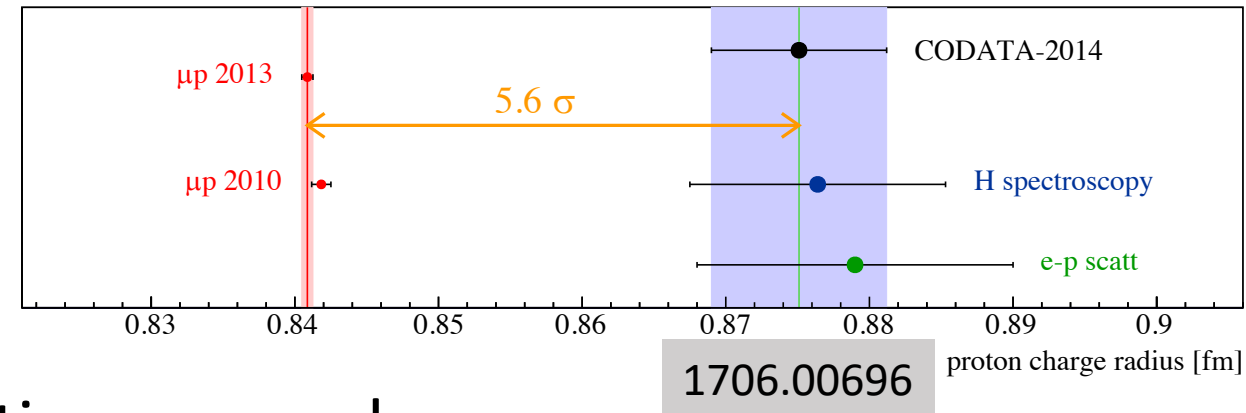
Where do we stand?

- Precision tests of the Standard Model
 - Measurements of masses and couplings
- Interplay of calculations and measurements
 - Accuracy on most cross sections $\gtrsim 5\%$
 - Limited by PDFs, QCD corrections
- Perturbative QCD as analysis tool
 - Jet substructure techniques
 - Data-driven background predictions



Where do we stand?

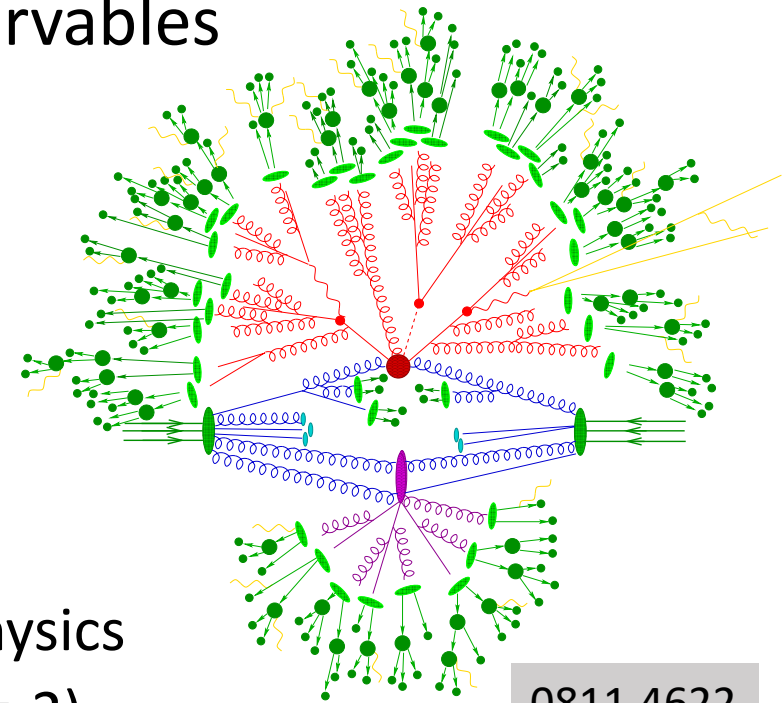
- QCD at strong coupling: diverse research program
 - Hadron physics, low-energy dynamics, heavy ions
 - Precision spectroscopy of light hadrons \leftrightarrow lattice QCD at high precision
 - Determination of hadron properties
 - Proton radius
 - Form factors
 - Nucleon structure



- Demands and drives new quantitative approaches
 - Understanding non-perturbative dynamics of QCD

Where do we stand?

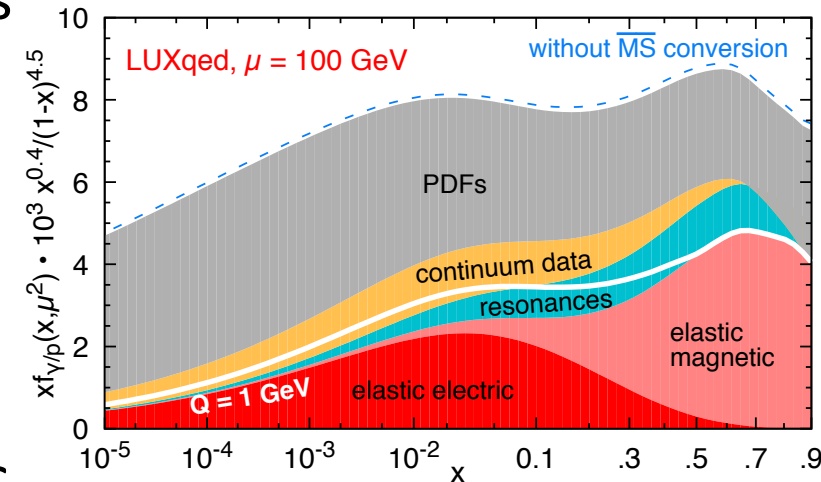
- Crucial interplay between QCD at strong and at weak coupling
- Non-perturbative effects on precision collider observables
 - Parton distributions
 - Intrinsic transverse momentum
 - Soft underlying event and hadronization
- Hadronic input to SM tests and BSM searches
 - Form factors in flavor physics
 - Hadronic cross sections in neutrino and astroparticle physics
 - Hadronic effects in QED precision observables: $\alpha(M_Z)$, $(g-2)_\mu$



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Where do we stand?

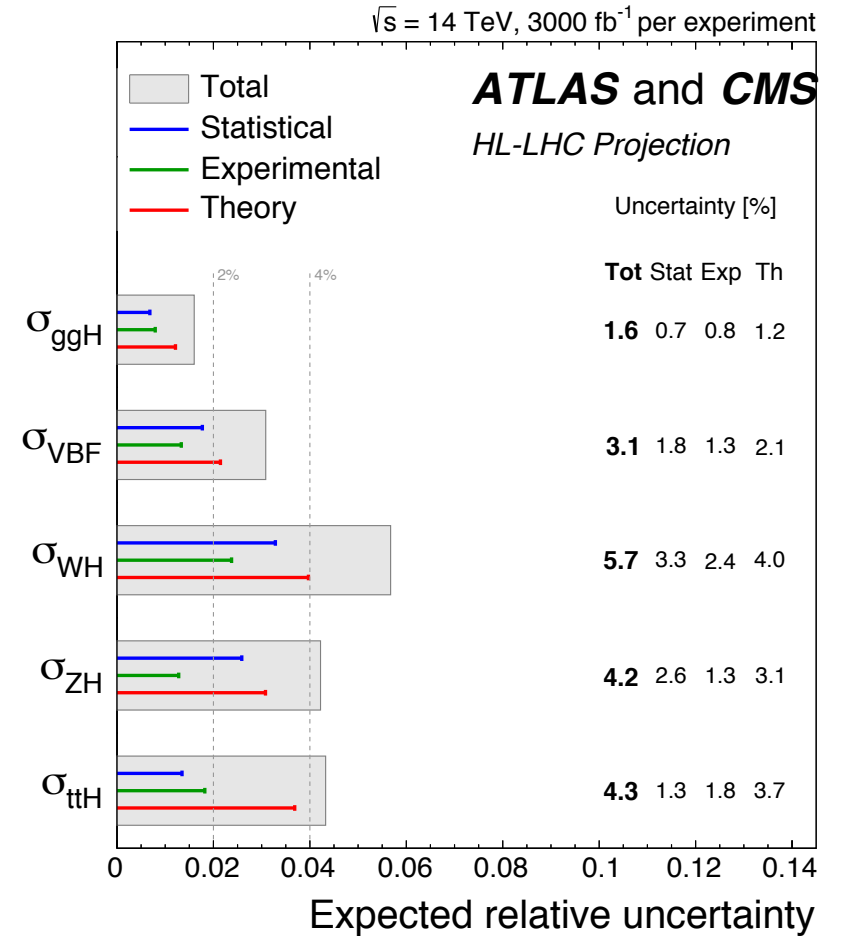
- Feed-in and feed-back between strong and weak coupling QCD
- Example: photon content of the proton (photon PDF)
 - Important ingredient to EW corrections of collider processes
 - Required for precision predictions at highest energies
 - Previously ad-hoc models with large uncertainty
 - LUXqed
 - relate to elastic and inelastic form factors
 - Exploit low-energy data
 - Combine with perturbative QCD evolution
- Different motivation to address similar questions



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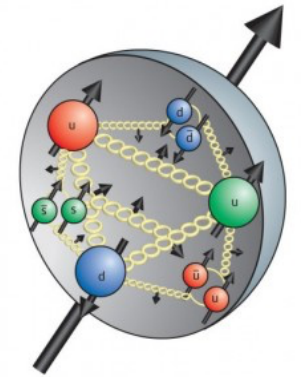
The challenges ahead

- Precision physics at HL-LHC and future high-energy colliders
- Aiming for ultimate precision in Standard Model tests and searches
 - Direct and indirect probes of physics at much higher energy scales
 - Sub-per-mille level precision on M_w , M_{top} , α_s
 - Requires major leaps in QCD+EW theory and experiment
- QCD theory into novel data analysis techniques



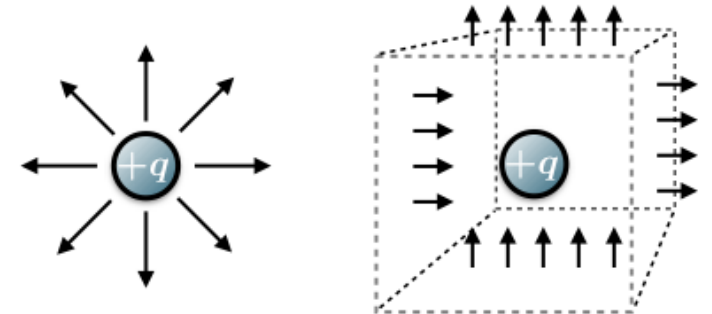
The challenges ahead

- Nucleon structure: parton distributions
 - Precision on large- x , highest- Q^2 , flavor decomposition
 - Reliable quantification of uncertainties (theory and experiment)
 - Ultimate precision on theory framework
- Establish three-dimensional nucleon structure
 - Spin-dependent parton distributions
 - Transverse-momentum structure
 - Semi-inclusive observables



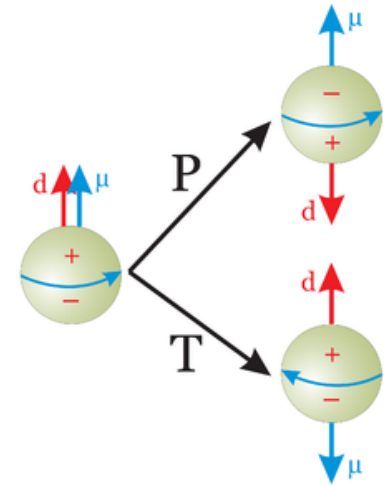
The challenges ahead

- Understand and predict hadronic cross sections
 - Soft production mechanisms in vacuum and QCD medium
 - Interplay with heavy-ion physics
 - Quantitative input for high-energy cosmic radiation, neutrino physics
- QCD predictions at strong coupling
 - Lattice QCD: improvements and novel applications
 - New methods and approaches
 - Towards first-principles understanding of parton-hadron transition, confinement



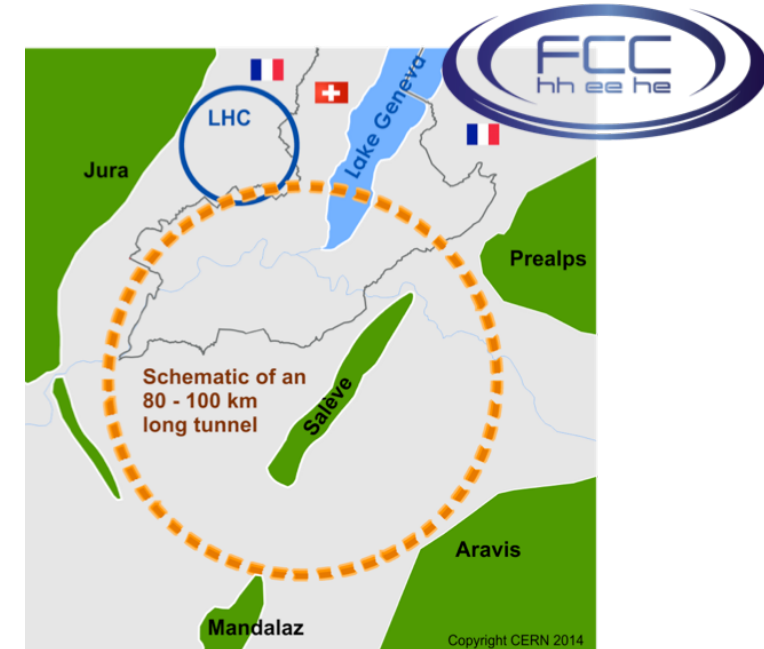
The challenges ahead

- Targeted precision studies at low energies
 - Searches for new physics:
QCD θ -term (strong CP-problem), charge radii
 - Antimatter spectroscopy
 - Exotic bound states: hadronic atoms, multi-quark states
 - QED-QCD interplay: hadronic vacuum polarization, light-by-light scattering
- Better exploit synergies between QCD at weak and strong coupling



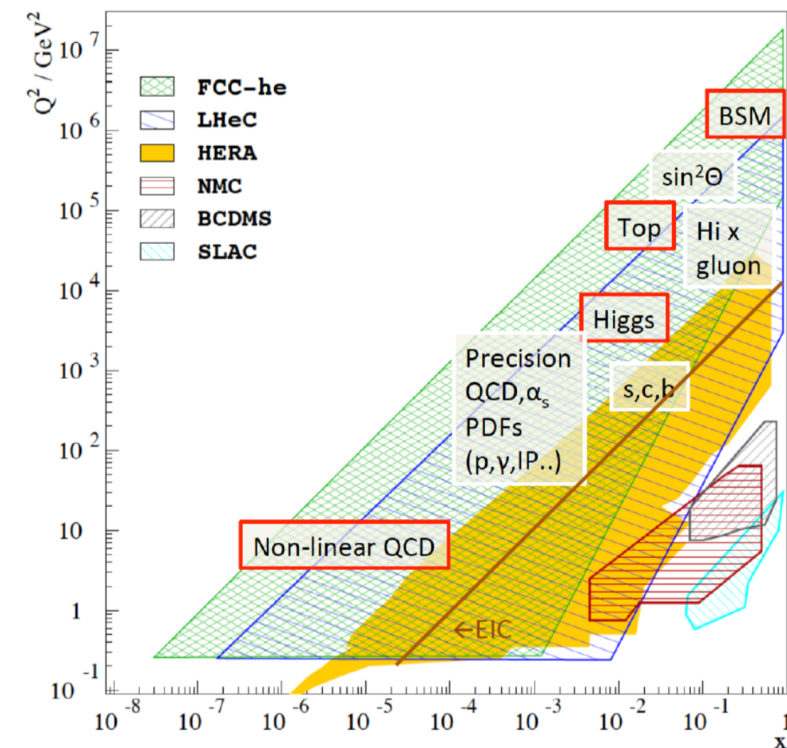
QCD at future facilities

- Highest-precision QCD program at FCC-ee/ILC/CEPC
 - Precision measurements, hadronization, light and heavy flavour spectroscopy
- High-energy frontier: HL-LHC and FCC-hh
 - Precision QCD predictions crucial to all aspects of physics exploitation
 - Open up new kinematical regimes for QCD studies
- Specific precision experiments at FNAL, PSI, CERN
 - muon and neutron programs, dipole moments



QCD at future facilities

- Lepton-hadron collisions from low to high energies
 - Elastic, inelastic and deeply inelastic scattering on fixed targets at PBC@CERN and JLab: nucleon interactions and structure
 - Medium-energy range EIC at BNL: 3D nucleon structure
 - High-energy frontier LHeC, FCC-eh: ultimate precision on PDF and QCD studies
- Fixed-target hadron physics program
 - PBC@CERN: spectroscopy, hadron structure
 - Fixed target at HL-LHC: benchmark processes



Directions of the QCD research community

- Optimal scientific exploitation of present and future measurements
 - QCD effects are ubiquitous in all areas of particle and astroparticle physics
 - Strive for highest accuracy and robustness in description and understanding
- Understanding of the strong interaction
 - Map out nucleon structure
 - Aim for first-principles predictions at strong coupling
- Large scientific diversity as a major strength
 - Fruitful interplay between research at strong and weak coupling